

## **Optimizing Refractivity from Clutter (RFC) for Surface-Based Ducts**

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### **LONG TERM GOALS**

Develop electromagnetic propagation models, and refractivity inversion algorithms, that perform equally well over land and sea and in the presence of anomalous propagation conditions for both surface and airborne emitters, for use in operational or engineering propagation assessment systems.

### **OBJECTIVES**

Develop an advanced unified hybrid radio propagation model based on parabolic equation and ray-optics methods for both surface-based and airborne applications. This model is named the Advanced Propagation Model (APM) and is the primary model used in the Advanced Refractive Effects Prediction System (AREPS). The specific technical objectives are to develop algorithms to extract surface clutter only from weather files provided by the Hazardous Weather Detection and Display Capability (HWDDC); and to improve, refine, and optimize the current state-of-the-art Refractivity From Clutter (RFC) algorithms to infer and characterize surface-based ducts (SBD).

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## APPROACH

In RFC, the duct-strength (range and height-dependent atmospheric index of refraction) is statistically estimated from the sea-surface reflected radar clutter. Genetic algorithms (GA) [1], importance sampler [2], and Markov chain Monte Carlo (MCMC) [3] samplers have been used to calculate the atmospheric refractivity from returned radar clutter. Although GA is fast and does well in estimating the maximum a posteriori solution, it gives poor results in calculating the multi-dimensional integrals required to obtain means, variances and underlying probability distribution functions of the estimated parameters. Accurate distributions can be obtained using MCMC samplers, such as the Metropolis-Hastings and Gibbs sampling algorithms. Their drawback is that they require a large number of samples relative to techniques such as GA and become impractical with increasing number of unknowns. The most recent work by Yardim, et. al. [4] demonstrates that the use of particle filters in RFC show much promise in tracking the spatial and temporal variations in the lower atmosphere over a maritime environment. We will continue this area of work in refining the RFC algorithms.

We are investigating in more detail the computation of the grazing angle within the APM to more accurately characterize the strength of the near-surface field, which is dependent on various propagating modes. These modes in turn are associated with variable grazing angles that, to date, have been largely overlooked and only the maximum grazing angle is taken at each PE range step. Accurate modeling of the grazing angles associated with the near-surface complex PE field is required for more accurate computation of surface clutter.

Much of the observed reflectivity from the U.S.S. Peleliu is indicative of evaporative ducting conditions. We investigated the feasibility of using our current RFC-ED algorithms to estimate evaporation duct height from the HWDDC.

Available data for validation of the RFC-SBD inversion algorithms is extremely limited. Therefore, collection of reflectivity and SNR data from the HWDDC installed on the SPS-48E radar located at Wallops Island, VA is planned.

## WORK COMPLETED

A rigorous approach has been developed to more accurately compute the grazing angles associated with various propagating modes under anomalous propagation conditions. This method is called “curved wave” spectral estimation and is based on the Wentzel-Kramers-Brillouin-Jeffreys (WKBJ) approximation to the electromagnetic wave propagation solution [5].

An RFC data collection effort was originally planned for the summer of FY11 to take place at Dam Neck, VA. However, due to the upgrade of their SPS-48E radar to the SPS-48G, the radar facility was inoperable for most of the year and our data collection effort has been postponed to FY12. We have diverted the FY11 funding resources for that effort to investigate the feasibility of using HWDDC to infer evaporation duct height (EDH). We have isolated weather/clutter data recorded from the USS Peleliu indicating strong evaporative ducting conditions and applied our RFC-ED algorithms to infer evaporation ducts from the SPS-48E observed clutter. We used shipboard logs of surface meteorological observations to compute evaporation duct heights and compared these with evaporation duct heights inferred from the observed clutter.

A data collection effort for June 2012 has been planned using the SPS-48E radar at the SCSC at Wallops Island, VA. This effort will support both the RFC task and “RF Performance Predictions for Real Time Shipboard Applications” task, which is also funded by ONR 32MM.

## RESULTS

### APM Grazing Angle

The current method of computing the grazing angle within the APM relies on ray tracing for over-water propagation paths. For mixed sea-land, or terrain paths, the grazing angles are computed based on a combination of ray tracing and plane wave spectral estimation. In both cases, particularly when ducting effects are being modeled, multiple grazing angles exist for a given range, and presently, only the maximum grazing angle within a range step is used to model rough surface effects and subsequently backscatter.

Classical angular spectral estimation assumes plane wave propagation with a constant wave speed along the array. The assumption of plane wave propagation yields a constant phase delay of  $\frac{2\pi}{\lambda} \Delta z \sin \theta$  between adjacent array elements where  $\theta$  is the grazing angle. Here,  $\lambda$  is the wavelength, and  $\Delta z$  is the PE mesh height. Currently, within the APM, the grazing angle is determined from identifying the peak location of  $B_{PWS}(\theta)$ , where  $B$  is defined under plane wave spectral (PWS) estimation as

$$B_{PWS}(\theta) = \sum_{l=0}^{N_a-1} w_l u_l e^{-jl \frac{2\pi}{\lambda} \Delta z \sin \theta},$$

where  $N_a$  is the number of array elements from the surface,  $l = 0$  corresponds to the array element index at the sea surface, and  $u_l$  is a complex value for the  $l^{\text{th}}$  element of the field array obtained from the PE solution to the wave equation.  $w_l$  are the weighting coefficients used, in this case, from a Hamming window.

In truth, for strong refractive gradients, particularly those associated with an evaporation duct profile, the phase delay between field elements is non-constant. Therefore, the inter-element phase delay for a non-constant wave speed along the array should be computed by integration of the vertical wavenumber along the array. Curved wave spectral estimation (CWS) is a method of nonplanar angular spectral estimation that matches to the curvature of waves imposed by a variable refractivity index. Here we use the Wentzel-Kramers-Brillouin-Jeffreys (WKBJ) approximation to the electromagnetic wave propagation solution, making the new form for  $B$

$$B_{CWS}(\theta) = \sum_{l=0}^{N_r} w_l u_l e^{-j \int_{z_0}^{z_l} k_v(z, \theta) dz},$$

where

$$k_v(z, \theta) = \frac{\omega}{c_0} \sqrt{n_m^2(z) - n_m^2(z_0) \cos^2(\theta)},$$

and  $n_m = n + \frac{z_0}{a_e}$ .  $k_v$  is the vertical wavenumber,  $n$  is the refractive index,  $a_e$  is the earth's radius,  $z_0$  represents the sea surface and  $N_r$  is the index of the highest array element (no greater than  $N_a$ ) where the condition  $k_v \geq 0$  is still satisfied. The end result when using the CWS method is that the various modes, or field strength as a function of angle from the surface, can be applied to the forward scatter PE solution to account for all grazing angles associated with propagating modes of different strengths. This provides for a more accurate forward scatter rough surface solution, and subsequently clutter.

Figure 1(a) shows the current PWS estimation procedure used in the APM and Figure 1(b) illustrates the more rigorous CWS estimation procedure. Figure 2 illustrates the difference in predicted clutter between the maximum [single] grazing angle method, and that of using the CWS method for a surface-based duct.

#### RFC-ED from HWDDC

Our current RFC-ED algorithms were previously validated using the SPY-1 radar onboard the USS Normandy. The antenna height for this radar is much lower, relative to mean sea level, than the SPS-48E radar onboard the USS Peleliu. Unlike the SPY-1 radar, where it's lower antenna height produces unique loss attenuation rates as a function of EDH, for the SPS-48E radar, propagation loss fall-off rates are fairly similar at higher EDHs (greater than 20 m). Therefore, there is an inherent limitation on EDHs that can be unambiguously estimated. Figure 3 shows the propagation effects for various EDHs using the SPS-48E geometry from the USS Peleliu. At EDHs greater than 25 m one can see the similarity in attenuation rates for ranges out to 40 km and greater.

Three days of recorded reflectivity data from the HWDDC (SPS-48E) onboard the USS Peleliu were isolated that were indicative of evaporative ducting. Shipboard logs of hourly recorded air temperature, sea temperature, wind speed, and humidity were used to compute evaporation duct profiles using the Navy Atmospheric Vertical Surface Layer Model (NAVSLaM), developed by the Naval Postgraduate School (NPS) [6]. The clutter and bulk meteorological observations analyzed were from 16-18 Feb 2006. The meteorological measurements were obtained by operational personnel and therefore subject to error. Following the methods described in [7], EDH errors were computed based on assumed errors in recorded temperatures, humidity, and wind speed. Assumed measurement error for both temperatures ( $T_{air}$ ,  $T_{sea}$ ) is  $\pm 0.5^\circ\text{C}$ , error for wind speed ( $U$ ) is  $\pm 0.5 \text{ m/s}$ , and assumed error for relative humidity ( $RH$ ) is  $\pm 3.0\%$ . The EDH error was computed for all combinations of bulk observation error,  $\delta$ , according to

$$\delta e_{dh}^p = \frac{|e_{dh}^{p_+} - e_{dh}| + |e_{dh}^{p_-} - e_{dh}|}{2},$$

$$\Delta e_{dh} = \left[ \sum (\delta e_{dh}^p)^2 \right]^{\frac{1}{2}},$$

where  $p_{\pm} = \pm \delta U$ ,  $\pm \delta T_{air}$ ,  $\pm \delta T_{sea}$ , and  $\pm \delta RH$ ;  $\delta e_{dh}^p$  is the EDH error associated with the error in the met parameter  $p$ , and  $\Delta e_{dh}$  is the total error in the modeled EDH based on the assumed measurement errors.

After isolating three days of recorded reflectivity data from the HWDDC, where EDs appeared evident, we reduced the data set further to exclude those times where extreme weather was present. Using the

point target removal algorithm developed in the first year under this effort, EDHs were estimated using our RFC-ED algorithm and compared with EDHs computed from shipboard surface observations. The results are shown in Figure 4. The mean,  $e_m$ , and weighted mean,  $e_w$ , RFC-estimated EDHs were computed as

$$e_m = \frac{S}{N_r} \sum_{i=1}^{\frac{N_r}{S}} EDH_s(i),$$

$$e_w = \frac{S}{N_r} \sum_{i=1}^{\frac{N_r}{S}} EDH_s(i) \frac{N_{az}(i)}{T_{az}(i)},$$

where  $S$  is the sector size (in this case, 9 radials),  $N_r$  is the number of total radials recorded per volume scan,  $EDH_s$  is the RFC-estimated EDH for the  $i^{th}$  sector,  $N_{az}$  is the number of usable data points within the  $i^{th}$  sector, and  $T_{az}$  is the number of total data points within the sector. Overall results were favorable; however, there appears to be a large discrepancy during UTC hours 20-24 for Feb. 16. A more complete analysis will be performed during next year's effort to include more time events indicative of EDs, along with removal of backscatter due to extreme weather.

#### *Data Collection Effort*

We have developed an experiment plan to obtain a comprehensive set of clutter data along with simultaneous in-situ bulk observations and upper air measurements at various ranges, using an SPS-48 radar with the HWDDC installed, in order to improve, refine, and optimize the current state-of-the-art RFC algorithms to infer and characterize SBD parameters. The experiment is being conducted along with a secondary field campaign to validate/develop a rain attenuation model using real-time rain rates from the HWDDC installed on the SPS-48 radar.

The RFC data collection is planned for a two week intensive operating period (IOP) from 18-29 June 2012 at Wallops Island, Virginia. The SPS-48E radar at the Ship Combat Systems Center (SCSC) at Wallops Island will be outfitted with the HWDDC and will be used for the entire duration of the IOP to collect clutter data in the form of universal format (UF) files. This will require NSWC-Port Hueneme Division, Virginia Beach detachment, to install the Weather Data Interface Card (WDIC) and SSC Pacific to install the HWDDC prior to the start of the IOP. To accommodate the secondary rain rate/attenuation effort, we require the SPS-48 radar, with the HWDDC, to operate from 4-29 June 2012. SCSC personnel are required to operate the SPS-48E radar and will do so in the course of normal operations for 9 hours per day, Monday through Friday of each week (approximate local time – 1030 to 1930).

In collaboration with NPS and NSWC-DD we will obtain in-situ observations of wind, temperature, and moisture as well as near-earth (<2 m) profiles of the boundary layer, and surface temperature. There will be two research vessels provided by NSWC-DD which will be used for longer range (30-60 km) radiosonde launching stations to observe and record upper air pressure, temperature, and humidity vertical profiles.

Bulk parameters will be measured from a buoy anchored off-shore from Building V-24 (SCSC SPS-48E radar site) at approximately 8-20 km range. The bulk measurements will be collected in support of analysis of surface clutter and propagation loss observed due to the evaporation duct.

## **IMPACT/APPLICATIONS**

The impact of this effort is that it will provide the U.S. Navy the capability to use through-the-sensor (TTS) technology to estimate low altitude refractive information in near real-time, and with sufficient spatial resolution, to provide timely and accurate radar performance assessment for naval operations. The propagation models and algorithms developed under this task will significantly aid in the overarching capability under the Weather-Radar-Through-the-Sensor (WRTTS) program to provide a completely integrated end-to-end “system of systems”.

The overall goal of this work is to produce operational RF propagation models for incorporation into U.S. Navy assessment systems. Current plans call for the APM to be the single model for all tropospheric radiowave propagation applications. As APM is developed it will be properly documented for delivery to the OAML, from which it will be available for incorporation into Navy assessment systems. Recent optimizations and enhancements of APM not only benefits the U.S. Navy but also **unifies** the overall military EM performance assessment capability by having a single high-fidelity propagation model that performs equally well over land and sea and in the presence of anomalous propagation conditions.

## **TRANSITIONS**

All APM modifications and added capabilities transition into the Tactical EM/EO Propagation Models Project (PE 0603207N) under PMW 120 which has funded the development of the Advanced Refractive Effects Prediction System (AREPS). Current and new software, along with information displays will also transition to PMW 120 and/or software projects for inclusion in the Naval Integrated Tactical Environmental Subsystem (NITES)-Next. Propagation modeling capabilities can also be transitioned to the Hazardous Weather Detection Display Capability (HWDDC) for use in future refractivity from clutter (RFC) integration plans.

Academia and other U.S. government are also utilizing APM/AREPS. The APM is currently being used by foreign agencies as the underlying propagation model within their own assessment software packages. The APM has also been adopted as the preferred propagation model in the Ship Air Defence Model (SADM), which is an operational analysis software tool developed to simulate the defense of a naval task group against multiple attacking anti-ship missiles and aircraft. BAE Systems, Australia are the developers of SADM and some of their customers include U.S. DoD agencies.

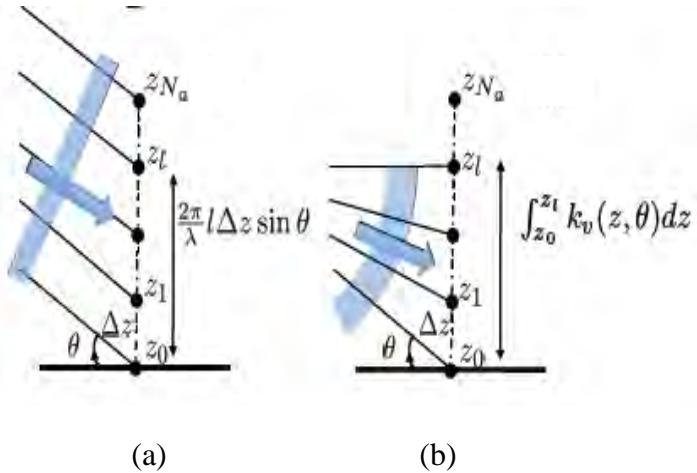
## **RELATED PROJECTS**

Efforts under this task are related to the Joint Tactical Radio System (JTRS) program and the Communication Assets Survey and Mapping (CASM) Tool. CASM is used Nationwide for planning and gap analysis of communications interoperability between state, local and Government agencies. It has been deployed to 77 urban areas across the Nation, and is expanding to statewide use. This tool was used during Operation Golden Phoenix for DoD and first responder communications planning and is currently

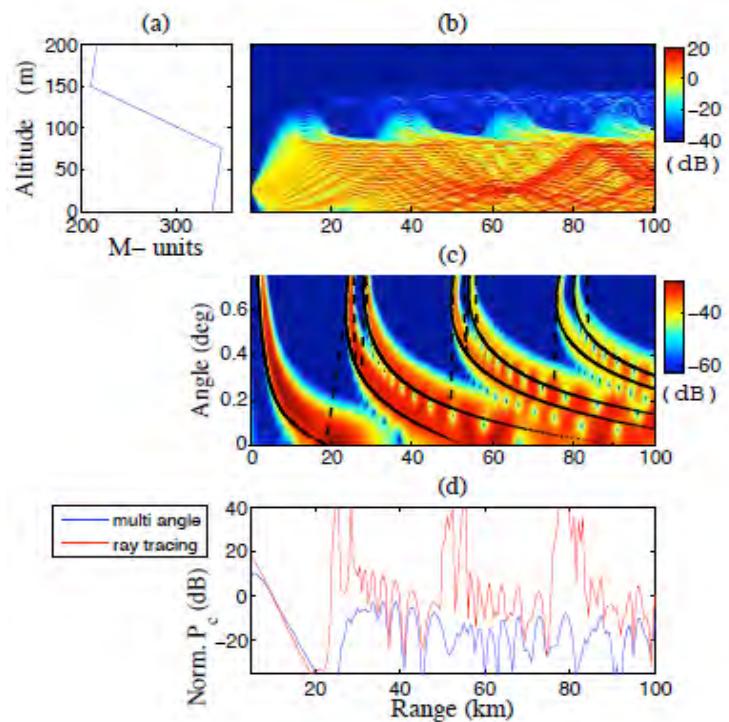
being investigated for use by the Navy Expeditionary Combat Command, the National Communications System, First Naval Construction Division, and the Naval Coastal Warfare Squadron, as well as other military components in Hawaii and Alaska.

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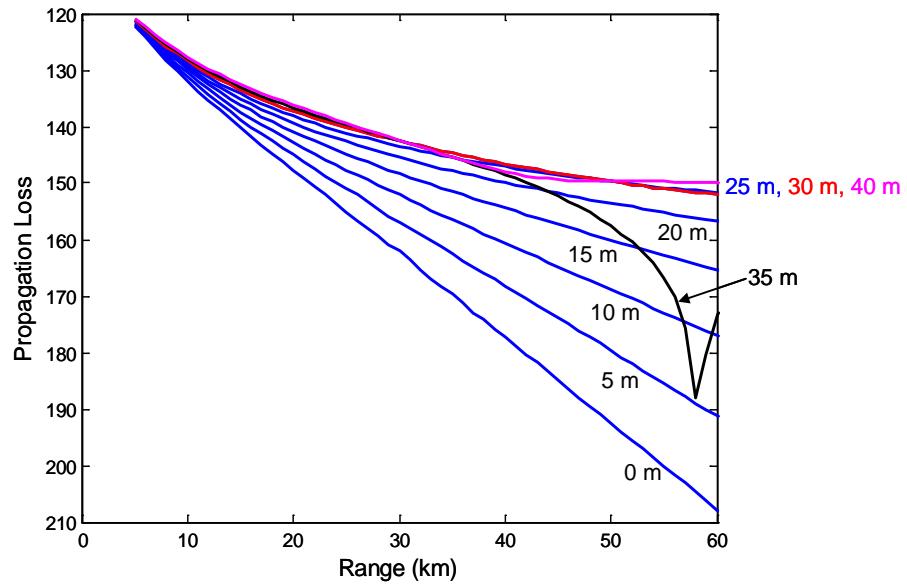
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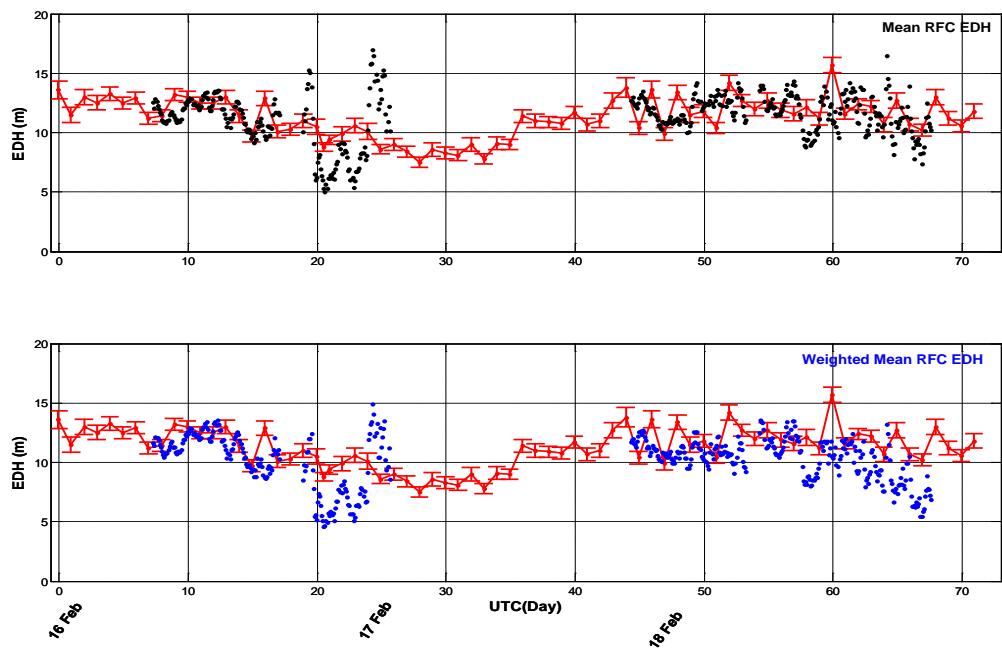
**Figure 1.** Spectral estimation procedure for computing grazing angle by (a) plane wave estimation, and (b) curved wave estimation.



**Figure 2.** (a) *M-profile of a surface-based duct.* (b) *Propagation factor F in dB for 10 GHz,* (c) *CWS output power overlaid with grazing angles obtained from ray tracing (solid) and maximum of ray traces (dashed).* (d) *Clutter power from maximum ray tracing and the multiple grazing angle model.*



**Figure 3.** Propagation loss vs. range for various evaporation duct heights for the SPS-48E radar onboard the USS Peleliu.



**Figure 4.** Comparison of RFC-estimated EDH (dots) and modeled EDH with computed errors (red). Top plot shows mean RFC results (black dots) and bottom plot shows the weighted mean RFC results (blue dots).

## PUBLICATIONS

Ali Karimian, Caglar Yardim, Peter Gerstoft, William S. Hodgkiss, Amalia E. Barrios, “Estimation of refractivity using a multiple angle clutter model”, submitted to *Radio Science*

Ali Karimian, Caglar Yardim, Peter Gerstoft, William S. Hodgkiss, Amalia E. Barrios, “Multiple Grazing Angle Clutter Modeling Using Curved Wave Beamforming”, submitted to *IEEE Transaction Antenna and Propagation*.

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